

Q. High-Temperature Aluminum Alloys

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Objectives

- Develop high-temperature aluminum alloys with adequate properties and shape capability for turbocharger compressor wheel and housing applications.

Approach

- Develop ternary phase compositions by modeling the equilibrium phase diagrams, casting alloys, and evaluating the properties of alloys identified.
- Perform physical and mechanical property measurements on specimens provided by the National Aeronautics and Space Administration (NASA) and by Eck Industries to characterize the material and determine the optimal properties possible with this method.
- Evaluate a nanophase particulate-reinforced aluminum alloy patented by Chesapeake Composites, Inc.

Accomplishments

- Accurately predicted and verified the binary phase diagrams of Al-Fe and Al-Mn and the ternary phase diagram of Al-Fe-Mn system using ThermoCalc.
- Found that the tensile strength of the NASA 388-T5 alloy exhibited almost 100% improvement compared with the currently used material.
- Demonstrated impressive high-temperature tensile strength, fatigue strength, and thermal stability for the dispersion-strengthened composite (DSC) material.

Future Direction

- Use ThermoCalc to generate the Al-Y-Yb ternary system and identify optimal compositions for casting trial and material property characterization.
- Evaluate NASA 388 alloy in T6 temper to achieve improved strength.

- Conduct fatigue tests, creep tests, notch sensitivity tests, and machinability studies of DSC material.

Introduction

The emission requirements for diesel engines mandate that turbocharger compressors be operated at significantly higher temperatures and pressures. This condition makes standard castable aluminum alloys unusable for next-generation turbocharger materials because their strength deteriorates at elevated temperatures. Therefore, there is a need to develop high-strength, high-temperature aluminum alloys to replace the standard alloys. Work at Cummins has identified three potential paths to improve the high-temperature strength and fatigue resistance of aluminum casting alloys. These paths have been partially investigated under cooperative agreement DE-FC05-97OR22582. Each path showed some promise, and further work is needed to determine the useful applications.

Approach

The scope of work in the program covers the investigation of three different paths to providing strength retention in aluminum alloys at high temperatures. Path 1 uses a ternary phase aluminum alloy using rare earth metals to provide precipitate size control and stability. Limited information on these alloys indicates that they offer high-temperature strength and stability; however, their predicted cost is high. Additional work was performed to determine if additional rare earth (or other metal) elements would produce beneficial properties at a reasonable cost. The main goal of this path is to generate the phase diagram of Al-Y-Yb using ThermoCalc software. Since there are few published data and little assessment of these rare-earth elements, a prudent approach demands that a systematic investigation be carried out.

Path 2 uses a conventional aluminum alloy that has been chemically modified by a

process developed at NASA-Huntsville. The elevated-temperature properties reported by NASA were attractive, but Cummins preferred an alloy with lower silicon for the compressor wheel application. Eck Industries purchased the license for the NASA-developed technology for the high-silicon casting alloy and has expanded the range to include conventional low-silicon casting alloys. Limited testing of these modified conventional low-silicon alloys at Cummins has not shown the property improvement anticipated. Currently, the NASA 388-T5 alloy is being evaluated to characterize the material and to determine possible process improvements.

Path 3 uses a particulate-loaded aluminum alloy patented by Chesapeake Composites, Inc. The nanophase particulates at 50 vol. % provided adequate high-temperature strength in early experiments; however, the particulate-loaded alloy could only be forged or squeeze cast, so its complex shape capability is limited. The mechanical behavior of this DSC material is being fully characterized. Casting modifications will be investigated to determine shape capability for the alloy.

Results

Path 1: Ternary Phase Aluminum Alloy Development

Although it is not presented, an extensive literature search has been carried out on the thermodynamic assessment of yttrium and ytterbium elements. The data collected so far are insufficient to predict the Al-Y-Yb alloy system; it is, however, a significant amount of information, which we expect to build upon. Figure 1 shows the phase diagram of the entire phase field of an Al-Mn system developed by ThermoCalc modeling. The predicted phases were verified with the

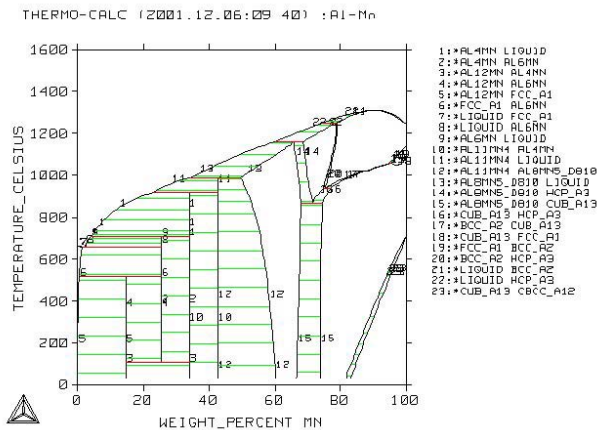


Figure 1. The phase diagram of the entire phase field of Al-Mn system generated using ThermoCalc.

binary phase diagram published by the American Society for Metals (ASM) (Figure 2).¹ The phase diagram of a binary Al-Fe system was also modeled and verified. The versatility of the software is clearly

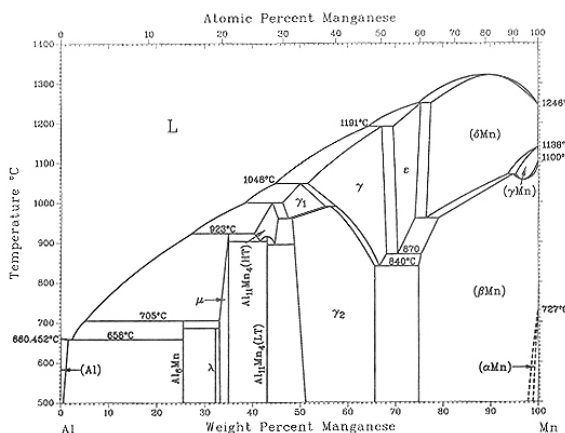


Figure 2. Al-Mn phase diagram (Source: *Binary Alloy Phase Diagrams*, 2nd edition, vol. 1, the American Society for Metals.)

demonstrated in the plotting of the phase diagrams. A major aspect of this project is to be able to examine the minute details of any region of interest, which happens to be the aluminum-rich region of the phase diagram. This type of plot simplifies the task of accurately determining the limits of the phase fields in the aluminum-rich corner (or

any region of interest) of the phase diagram. The ternary phase diagram of Al-Fe-Mn was further developed by using ThermoCalc software. Figure 3 displays the ternary Al-Fe-Mn phase diagram at 1000°C. The versatility of ThermoCalc was demonstrated. The software will be used to predict binary Al-Y and Al-Yb systems. Eventually, the ternary phase diagram of the Al-Y-Yb system will be modeled. Optimized chemical compositions will be selected to produce stable phases to achieve high-temperature strength and thermal stability in the new ternary phase alloy.

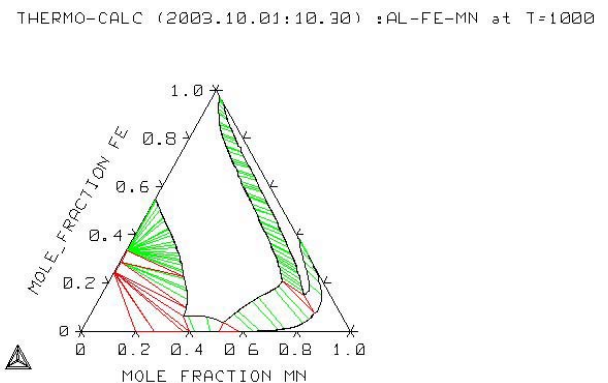


Figure 3. Al-Mn-Fe phase diagram at 1000°C, developed by ThermoCalc modeling.

Path 2: NASA 388-T5 Aluminum Alloy

The NASA 388-T5 alloy is similar to the A384.0 and A413.0 alloys. It is a heat-treatable Al-Si (~12%) alloy for high-ductility, high-strength, and hardness applications at elevated temperatures. The main alloying elements are Si, Cu (5.5–8.0), Fe (0.8 max.), Mg (0.5–1.5), Ni (0.05–1.2), Mn (1.0 max.), Ti (0.05–0.12), Zr (0.12–1.2), V (0.05–1.2), Zn (0.9 max.), P (0.001–0.1). Potential applications include high-performance pistons for gasoline and diesel engines; turbocharger compressor wheels and housings; cylinder blocks; air-cooled engines; and compressors and pumps requiring high wear resistance, low coefficient of thermal expansion, low dimensional distortion, and

superior tensile and fatigue strengths at elevated temperatures.

Test plates (1 × 6 × 12 in.) of NASA 388-T5 alloy were cast by Eck Industries for tensile and fatigue tests. Samples were thermally soaked at test temperatures for 500 hours prior to testing. Figure 4 shows the tensile test results as a function of temperature. The tensile strength of NASA 388-T5 alloy was about 15 ksi and 10 ksi at 260°C (500°F) and 316°C (600°F), respectively. For comparison purposes, the tensile strength of the currently used turbo impeller material, C355, was also plotted. However, since no in-house data on C355 are available, the tensile data of C355 from *Alloy Digest* were used for comparison. The tensile strength of the NASA 388-T5 alloy at 260°C (500°F) and 316°C (600°F) after 500 hours of thermal soaking was much higher than that of the C355 alloy with no thermal soaking. This indicates that the tensile strength of the NASA 388-T5 alloy is improved by almost 100% compared with the C355 alloy that currently is used.

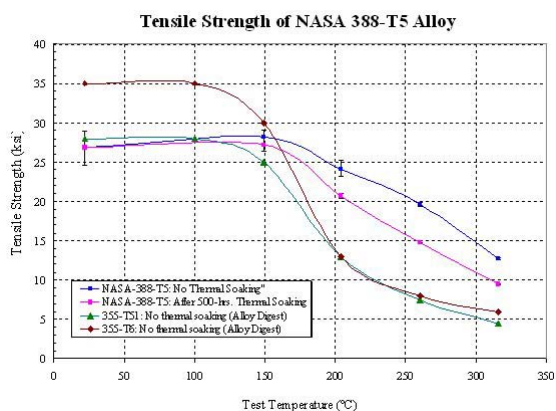


Figure 4. Tensile strength of NASA 388-T5 alloy at elevated temperatures.

Path 3: Particulate-Reinforced Alloy

This task involves a nanophase particulate-loaded aluminum alloy patented by Chesapeake Composites. A patented, low-cost, liquid metal infiltration process is used to produce a billet form ready for secondary operations. This composite material

combines the enhanced elevated-temperature strength, toughness, and ductility of dispersion-strengthened alloys with the stiffness and low coefficient of thermal expansion of metal matrix composites. It is claimed that this composite can be readily turned using tungsten carbide tooling and drilled and tapped using high-speed steel tools. Potential applications include pistons, compressor wheels, and engine components.

Three as-infiltrated billets of the DSC with 1090Al matrix and a 40 vol. % fraction of nanoscale Al_2O_3 particles were supplied by Chesapeake Composites for initial evaluation. Tensile specimens were prepared from the billets and thermally soaked at 204°C (400°F), 260°C (500°F), 316°C (600°F), and 371°C (700°F) for 500 hours prior to testing. Figure 5 shows the tensile test results for the DSC material at elevated temperature.

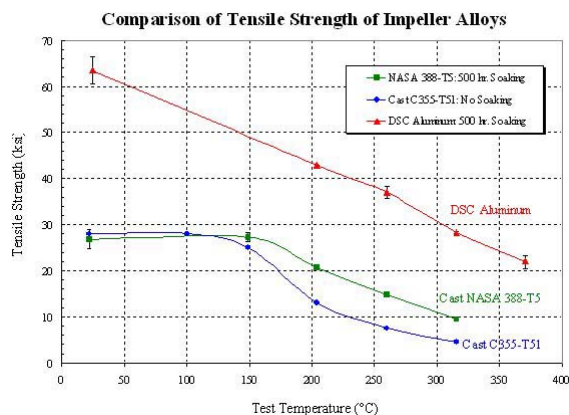


Figure 5. Comparison of tensile strength of DSC and other aluminum alloys.

As can be seen, although the tensile strength decreases nearly linearly with temperature, values as high as 20 ksi are obtained at 371°C (700°F), which is quite impressive for an aluminum alloy. For comparison purposes, the tensile strengths of the NASA 388-T5 alloy and C355-T51 alloy were plotted. The elevated-temperature tensile strength of the DSC material is consistently higher than that of any other two alloys. The tensile strength of the DSC material was also tested after

500 hours of long-term thermal soaking at test temperatures. Essentially no reduction in the tensile strength of the DSC material was observed. This indicates that the DSC material exhibited very good thermal stability even after long-term usage at high temperatures.

Rotating beam fatigue tests of 2024Al-DSC and NASA 388-T5 alloy were conducted at various temperatures. Figure 6 shows the fatigue test results at 260°C (500°F). The fatigue strength of the DSC material was determined to be far superior to that of NASA 388-T5 alloy. The DSC material obtained very impressive fatigue strength of 19 ksi at 10^7 cycles.

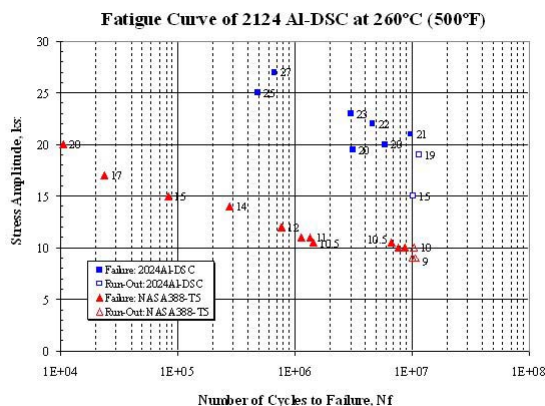


Figure 6. Rotating beam fatigue strength of DSC and NASA 388-T5 alloys.

Conclusions

Three different paths were adopted to develop and evaluate high-temperature aluminum alloys for turbocharger compressor wheel and housing applications. The versatility of the ThermoCalc software was demonstrated in the plotting of the phase diagrams. The Al-Y-Yb ternary system will be modeled. The NASA 388-T5 alloy exhibited significantly improved elevated-temperature strength compared with the material currently used. We will investigate whether the use of T6 temper results in continued improvements in strength. The DSC material exhibited very impressive high-temperature tensile and fatigue strength. Both the NASA 388-T5 alloy and the DSC material have high potential for use to replace C355 to achieve improved material strength and thermal stability. Other important material properties such as creep resistance, notch sensitivity, and machinability will be further evaluated.

References

Binary Alloy Phase Diagram, Ed. T. B. Massalski, 2nd ed., Vol.1, the American Society for Metals, 1996.